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Are passive red spirals truly passive? *(Research Note)*

The current star formation activity of optically-red disc galaxies

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ABSTRACT

We use GALEX ultraviolet and WISE 22 μm observations to investigate the current star formation activity of the optically-red spirals recently identified as part of the Galaxy Zoo project. These galaxies were accurately selected from the Sloan Digital Sky Survey in order to be pure discs with low or no current star formation activity, representing one of the best optically-selected samples of candidate passive spirals. However, we show that these galaxies are not only still forming stars at a *significant* rate ($\gtrsim 1$ M$_\odot$ yr^{-1}) but, more importantly, their star formation activity is not different from that of normal star-forming discs of the same stellar mass (M$_* \gtrsim 10^{10.2}$ M$_\odot$). Indeed, these systems lie on the UV-optical blue sequence, even without any corrections for internal dust attenuation, and they follow the same specific star formation rate vs. stellar mass relation of star-forming galaxies. Our findings clearly show that, at high stellar masses, optical colours do not allow to discriminate between actively star-forming and truly quiescent systems.

Key words. Galaxies: evolution – Galaxies: photometry – Galaxies: star formation – Ultraviolet: galaxies – Infrared: galaxies

1. Introduction

Since its discovery, the colour vs. magnitude (or stellar mass) relation (e.g., Visvanathan & Sandage 1977; Visvanathan 1981) has been adopted as one of the most useful tools to characterize the properties of galaxies across the Hubble time. Particularly powerful is the use of colours to discriminate between late-type/star-forming systems and early-type/passive galaxies, when accurate morphological classification is not available. However, it is now well known that the bimodality in the colour distribution of galaxies does not always reflect a difference in morphological type (Scodeggio et al. 2002; Franzetti et al. 2007). Indeed, at least in the local Universe, blue/star-forming spheroids (e.g., Yi et al. 2005; Kannappan et al. 2009; Schawinski et al. 2009) and red/quiescent spirals (e.g., van den Bergh 1976; Moran et al. 2006; Crowl & Kenney 2008; Cortese & Hughes 2009; Wolf et al. 2009; Bundy et al. 2010; Rowlands et al. 2012) do exist.

In the last decade, we have seen a rapid increase in the number of studies focused on such unusual systems with the aim to understand why they do not follow the typical relations between morphology and colours. However, while identifying current star formation activity in elliptical galaxies is relatively easy, isolating truly quiescent disc galaxies is a more complicated issue. Indeed, optical red colours do not always automatically imply a passive stellar population (e.g., Cowie & Barger 2008; Cortese & Hughes 2009). Dust extinction and a large bulge component are among some of the issues that can significantly affect the observed optical colours of discs, making them appear much more 'evolved' then they really are. For these reasons, the vast majority of the works focused on truly passive spirals have taken advantage of multiwavelength datasets spanning from the ultraviolet to the mid- and far-infrared regime, in order to account at least for the effects of internal dust absorption (e.g., Wolf et al. 2009; Gallazzi et al. 2009).

Recently, as part of the Galaxy Zoo project (Lintott et al. 2008), Masters et al. (2010, hereafer M10) performed a careful selection to isolate and study red spirals. They take advantage of the morphological classification available for thousands of objects to select spiral galaxies and then adopt a simple cut in inclination, optical colour and bulge fraction to identify disc-dominated objects which should be 'truly passive' (i.e. with current star formation activity significantly lower than the one observed in normal spiral galaxies of similar stellar mass). The novelty of this technique lies in the fact that only optical data, combined with an accurate morphological classification, are needed to isolate the red spiral population. If successful, these selection criteria may make significantly easier to isolate passive systems, thus improving our understanding of the evolutionary paths leading to such unusual galaxies.

Thus, in this Research Note we take advantage of Galaxy Evolution Explorer (GALEX, Martin et al. 2005) ultraviolet (UV) and Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) 22 μm observations to study the star formation properties of these optically-red spiral galaxies and to determine whether they are really passive.

2. The data

The sample of optically-red spirals presented by M10 comes from the Galaxy Zoo clean catalogue (Lintott et al. 2008), which is based on the Sloan Digital Sky Survey (SDSS) DR6 (Adelman-McCarthy et al. 2008). First, a volume-limited sample of spirals was obtained assuming spiral likelihood[1]

[1] This corresponds to the fractional number of cases in which a galaxy has been classified as a spiral by the public.

(Bamford et al. 2009) greater than 0.8, spectroscopic redshift $0.03 < z < 0.085$ and r-band absolute magnitude $M_r < -20.17$ mag. Secondly, bulge-less and face-on discs were selected requiring a ratio between the major and minor axis of the galaxy $\log(a/b) < 0.2$ and a fraction of the light coming from the deVaucoleur component of the surface brightness profile $fracDev < 0.5$. Finally, red spirals were defined as those objects having a color $(g-r) > 0.63 - 0.02 \times (M_r + 20)$. The sample of red spirals so obtained includes 294 galaxies.

Unfortunately, not all the galaxies in the M10 sample are included in the GALEX GR6 public release. Thus, in the following analysis, we only focus on the subset of 255 galaxies observed by GALEX and lying within 0.55°from the center of a GALEX tile, in order to avoid edge effects[2]. Given that this subset includes ~87% of the original sample, we are confident that our conclusions can be extended to the whole population of optically-red galaxies studied by M10.

2.1. GALEX & WISE photometry

We cross-correlated the 255 red spirals with the WISE all-sky survey source catalogue using a matching radius of 10 arcsec. We found 233 galaxies detected at 22 μm but, after a careful visual inspection of the images, 46 turned out to be spurious or marginal detections, or in regions highly contaminated by foreground emission. Thus, out of the 255 galaxies in our sample, 166 (~65%) are clearly detected at 22 μm.

In order to obtain homogeneous flux density estimates in the GALEX UV and WISE 22 μm bands, we performed aperture photometry using the same aperture size in all images. We adopted circular apertures of size twice the isophotal diameter at the 25 mag arcsec^{-2} level in r band, convolved to the WISE 22 μm resolution (12 arcsec). In a few cases, the size of the aperture has been adjusted to make sure that all the emission from the galaxy is included. Sky background was determined in circular annuli or boxes around the target, and foreground/background objects were accurately masked.

All the 255 galaxies in our sample are detected in near-ultraviolet (NUV), while only for 220 objects (86% of the sample) we were able to obtain a far-ultraviolet (FUV) flux density. This is mainly because the FUV observations are in general less sensitive than the NUV ones. By comparing the magnitudes obtained from independent observations of the same galaxy, as well as with the GALEX GR6 public catalogue, we obtain a typical uncertainty of ~0.15 and 0.30 mag in NUV and FUV, respectively. Similarly, we find a very good agreement between our flux densities and the *standard* aperture estimates (w4MAG) in the WISE all-sky survey catalogue, with a typical scatter of ~0.2 mag.

UV magnitudes have been corrected for Galactic extinction following Wyder et al. (2007). No aperture or colour corrections were applied to the 22 μm flux densities. These are in general smaller than the uncertainty on the flux density, and thus do not affect our results.

3. Results

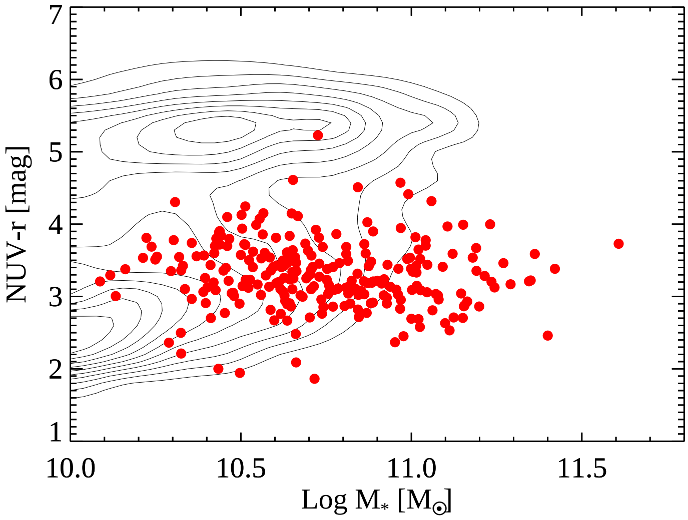

Fig. 1. The optically-red spirals (red circles) on a $NUV-r$ vs. stellar mass diagram. The contours show the distribution of galaxies in the GASS survey (Catinella et al. 2010).

Fig. 1 shows where the red spirals (red filled circles) lie in a $NUV-r$ colour vs. stellar mass (M_*) diagram. Stellar masses are taken from the MPA/JHU SDSS DR7 release[3]. These are derived from SDSS photometry using the spectral energy distribution fitting technique described in Salim et al. (2007), assuming a Chabrier (2003) initial mass function (IMF). The black contours show the colour distribution of the parent sample of the GALEX Arecibo SDSS survey (GASS, Catinella et al. 2010), a volume-limited sample of nearby massive galaxies ($M_* > 10^{10}$ $M_\odot$), providing an indication of the typical range of UV colours of red- and blue-sequence massive galaxies in the local Universe.

It is clear that the red spirals in M10 sample are not quiescent. Not only there is just one galaxy in the UV red sequence, but almost all the sample (94%, i.e., 240 out of the 255 galaxies) have an observed $NUV-r$ colour bluer than 4 mag, i.e., the typical value observed in actively star-forming galaxies (e.g., Salim et al. 2007).

In order to determine if the current star formation activity of these optically-red spirals is different from that of normal star-forming galaxies of similar stellar mass, we determined star formation rates (SFRs) by combining the GALEX UV and WISE 22 μm data. We used the 22 μm fluxes to correct the NUV and FUV luminosities for dust attenuation following Hao et al. (2011):

$$\begin{aligned} L(NUV)_{corr} &= L(NUV) + 2.26 \times L(22\mu m) \\ L(FUV)_{corr} &= L(FUV) + 3.89 \times L(22\mu m) \end{aligned} \tag{1}$$

where L are luminosities in units of erg s^{-1}. It is important to note that these relations were calibrated using Spitzer 24 μm and IRAS 25 μm flux densities, whereas in this case we are applying them to the WISE 22 μm emission. Given that, for typical star-forming objects, the 22 μm emission should be comparable or slightly fainter than the 24 μm flux density, we can assume our corrections to be a lower limit to the real value. For galaxies observed but not detected by WISE we considered two different extreme cases by either fixing the 22 μm emission to zero or to the typical 3σ sensitivity limit of WISE (i.e. 3 mJy). We then estimated the current SFR from the corrected UV luminosities using the relation presented by Salim et al. (2007) and calibrated on a Chabrier (2003) IMF

$$SFR\,(M_\odot yr^{-1}) = 1.46 \times 10^{-28} \times L_\nu \tag{2}$$

[2] Only 7 galaxies in the sample have been observed but lie at distances greater than 0.55°.

[3] `http://www.mpa-garching.mpg.de/SDSS/DR7/`

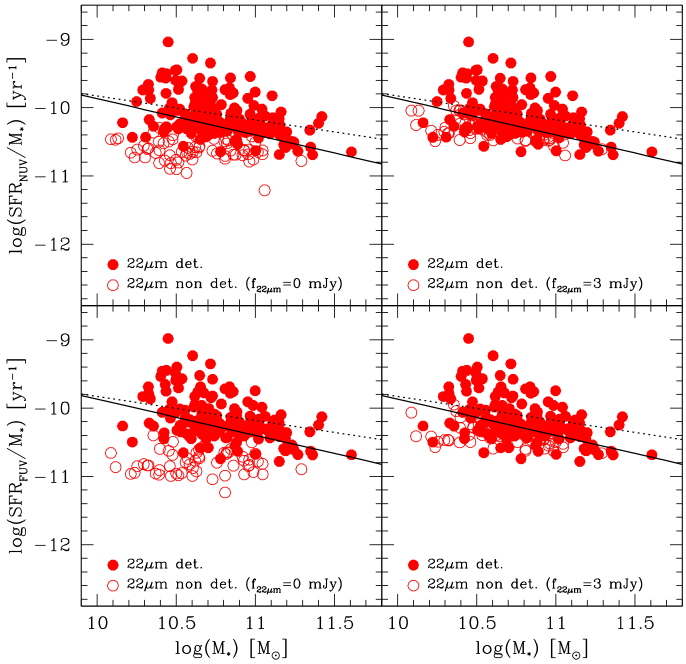

Fig. 2. The NUV- (top) and FUV-based (bottom) specific star formation rate vs. stellar mass relation for the sample of optically-red spirals. Filled and empty circles show 22 μm detections and non detections, respectively. For non detections, the SFR has been determined by assuming a 22 μm flux density equal to zero (left panels) or to 3mJy (i.e., $\sim 3\sigma$ WISE detection limit; right panels). The dotted and solid lines show the best-fit to the star-forming sequence obtained by Salim et al. (2007) by including only star-forming galaxies (i.e., excluding galaxies with optical lines ratios typical of active galactic nuclei) or all galaxies with $NUV - r$ colour lower than 4, respectively.

where L_ν is in units of erg s^{-1} Hz^{-1}. The SFRs estimated from the NUV and FUV luminosities agree within ~10-25%, with the NUV-based SFR being typically higher by ~0.03-0.07 dex.

In Fig. 2 we plot the specific star formation rate ($SSFR = SFR/M_*$) as a function of the stellar mass for the M10 sample. The top and bottom panels show the results obtained for the NUV-based and FUV-based star formation rates, respectively. For each row, the difference between the left and right panels is in the treatment of the WISE non detections. While in the left panels the 22 μm flux density is set to zero, in the right ones it is equal to the typical 3σ noise level of WISE images. Thus, the two panels show the two extremes, with the real relation followed by this sample lying in between the two plots.

As expected from what already shown in Fig. 1, and regardless the way we treat non detections, all the red spirals are forming stars at a significant rate and ~85-90% (depending on which SFR estimate is used) have a current $SFR \geq 1$ M$_\odot$ yr^{-1}. More importantly, the M10 sample follows remarkably well the relation obtained for nearby star-forming galaxies by Salim et al. (2007, solid and dashed lines in Fig. 2), implying that these galaxies are not different from the local population of blue sequence discs.

4. Discussion & Conclusion

The results presented in the previous section clearly show that the red spirals in the M10 sample are not passive but are still forming stars at the rate expected for their stellar mass. It is thus important to briefly discuss why the very careful optical selection performed by M10 did not isolate truly quiescent systems.

We can safely exclude that dust attenuation plays a dominant role. The selection of face-on spirals guarantees the absence of highly obscured systems, as clearly shown in Fig. 1. Indeed, dust extinction would affect much more heavily the UV colours moving all the galaxies to the UV red sequence, contrary to what observed.

In order to understand why these objects have optically-red colours, despite their still on-going star formation activity, it is important to remember that they are massive galaxies. For stellar masses $\gtrsim 10^{10}$ M$_\odot$, the optical blue cloud merges into the red sequence, suggesting that optical colours are no longer a good proxy for the current star formation activity of a galaxy. Indeed, as extensively discussed by Wyder et al. (2007), in UV the blue and the red sequences are well separated even at high luminosities, implying that massive spirals are forming stars despite what suggested by their optical colours. This is, at least partially, a consequence of the fact that massive objects formed the bulk of their stars at earlier epochs than dwarf galaxies (e.g., Boselli et al. 2001; Gavazzi et al. 2002; Heavens et al. 2004; Thomas et al. 2010), and that optical colours are more directly related to the average age of the stellar populations than to the current star formation activity (e.g., Wyder et al. 2007; Chilingarian & Zolotukhin 2012). The fact that the fraction of the optically-red spirals in the M10 sample significantly increases with stellar mass (see Fig. 2 of M10) is consistent with this scenario.

In conclusion, at least at high stellar masses, optical colours alone are not sufficient to discriminate between actively star-forming and quiescent systems.

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